AIR WATCH - Air induced fluorescence by radiation: Laboratory experiments.

S. Giarrusso[a], O. Catalano[a], F. Celi[a], G. Fazio[a], G. La Rosa[a], G. Richiusa[b], T. Schillaci[b], G. Bonanno[c], R. Cosentino[c], R. Di Benedetto[c], S. Scuderi[c]

[a] Istituto di Fisica Cosmica ed Applicazioni dell'Informatica - CNR, Palermo, Italy.
[b] Dipartimento di Energetica e Applicazioni di Fisica - Universita` di Palermo, Palermo, Italy.
[c] Osservatorio Astrofisico di Catania, Catania, Italy.

ABSTRACT

We report preliminary measurements of the air UV fluorescence light yield as a function of pressure using as a stimulus hard X-rays. For comparison measurements in pure nitrogen are also reported. Knowledge of the air UV fluorescence light yield induced by hard X-rays is needed in order to evaluate the capability to detect, in an AIRWATCH FROM SPACE experiment, Gamma Ray Burst (GRB) events. The experiment was carried out at the LAX X-ray facility in Palermo, by using an high flux collimated X-ray photon beam. The experimental results indicate that the fluorescence yield is inversely proportional to the filling pressure. At pressures below 30 mbar, corresponding to the value for the upper atmospheric layers in which the X and gamma ray photons of the GRBs are absorbed, about 0.1 % of the total energy of a GRB is transformed in UV photons. This makes possible the observation of the GRBs with the technique proposed in the AIRWATCH FROM SPACE experiment.

Keywords: Cosmic Radiation, Gamma Ray Bursts, Atmosphere, Fluorescence, Space mission.

1. INTRODUCTION

The atmospheric UV fluorescence associated with the Extensive Air Showers produced by the High Energy Cosmic Rays primaries is the basic phenomenon for the ground based experiments Fly's Eye[1] and HiRes[2,3]. The detection from space (with an artificial satellite orbiting at height of 500-600 Km) of the UV fluorescence induced in the atmosphere by the Cosmic Radiation was suggested several years ago' by John Linsley[4]. The large effective area (up to millions Km^2*sr) and the target mass (up to 10^{13} tons) offered by the Earth Atmosphere observable from Space, make it the ideal detector for the Extreme Energy Cosmic Radiation (EECR with $E>10^{19}$ eV) characterized by an extremely low flux and, in the case of neutrinos, by a very weak interaction cross section.

Another conspicuous phenomenon interesting the interaction between the Earth Atmosphere and the Extraterrestrial Radiation is represented by the Gamma Ray Bursts (GRB) . The GRBs have typical spectra extending from few keV to several hundreds keV or up to the GeV in some cases of particularly hard and intense GRB. The total energy of GRB impacting with the atmosphere is absorbed by the upper atmospheric layers below about 30 mbar residual pressure (30-50 Km height). A fraction of the absorbed energy is released in an UV flash of the GRB duration (from few msec up to tens of seconds) and of intensity proportional to the total GRB energy. The association of the GRBs with cosmological sources releasing energies as high as 10^{51}- 10^{52} ergs, as implies by the observations of the X, optical and radio afterglow made possible by the BeppoSAX findings for the arrival direction, suggests the existence of a possible connection between GRBs and the EECR[5]. A direct test could be provided by the observation of a coincidence in direction and time, between a GRB and a "EECR neutrino", the choice of the neutrino being imposed to avoid the restriction of GZK[5] cut-off for hadrons and Gamma Rays, coupled with the time delay for particles with mass significantly different from zero.

Gamma ray photons are absorbed via photoelectric effect by the molecules of the air (primarily Nitrogen and Oxygen) producing primary electrons with energy equal to the gamma photons. These in turn produce secondary electrons with lower energy (from few to hundreds eV) that excite or ionize the air molecules.

The UV fluorescence radiation from air results almost entirely from electronic transition from the first excited levels of the Nitrogen molecule (N_2) or molecular ion (N_2^+) to the ground level. The radiative emission from these electronic transitions is detected as very narrow lines in the near UV band (mainly lines 337, 357 for N_2 and 391 nm for N_2^+).

Due to highly competitive non-radiative processes the UV fluorescence Light Yield, defined as the fraction of the energy of the gamma photon that goes into UV fluorescence photons, is expected to be low (well below 1%). Experimental measurements have been carried out in the past using relativistic electrons with energies above 1 MeV up to few GeV, or electrons of 50 keV, all confirming the low fluorescence efficiency of the air[6,7].

In the framework of the AIRWATCH FROM SPACE experiment, lab measurements of the UV yield in air, induced by X or gamma ray photons, are crucial for estimating the correct parameters and sensibility to observe the GRBs..

In the present paper we report preliminary experimental results obtained in air and, for comparison, in pure nitrogen using an intense flux of X-ray photons. We show that at the pressures of our interest (below 30 mbar) the UV light yield of the air is sufficient to make possible the observation of GRBs, in AIRWATCH FROM SPACE experiment.

2. EXPERIMENTAL SET UP

To measure the UV fluorescence yield of the air we have chosen to use the same technique adopted in the past in our lab to detect primary UV scintillation in Xenon[8].

The experimental set up including the detection system and the electronic chain is sketched in figures 1 and 2.

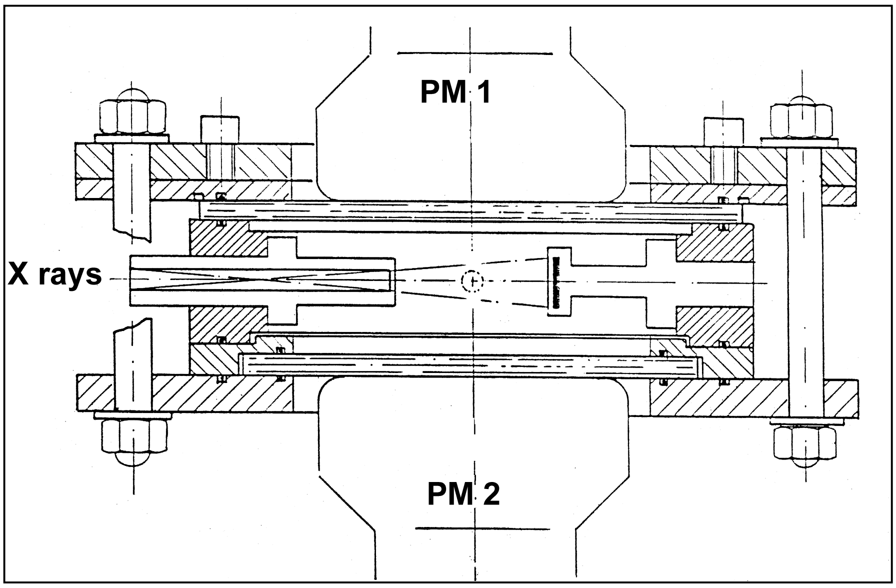

Fig. 1 Schematic of the gas cell.

The apparatus of measurement[9] consists of a cylindrical gas cell of ceramic closed at top and bottom by quartz windows 5 mm thick. Two photomultipliers (EMI D319Q operated at 2 kV) of 8 cm of diameters detect the UV light produced inside the cell. To reduce the variations of the solid angle subtended by the photomultipliers (Pmts) at point production of the UV light, the X-ray photons are collimated inside the cell in an absorption region of only 4 cm of length centered on the Pmts.

The distance between the UV production and the quartz window is 2.2 cm both side. The two Pmts are used in coincidence mode to detect the UV photons produced at any X-ray absorption, thus eliminating spurious trigger signals due to the uncorrelated noise of the Pmts. As the fluorescence decay time of the excited N_2 molecules is about 50 nsec[10], we have chosen in the electronic chain a coincidence gate time of 500 nsec.

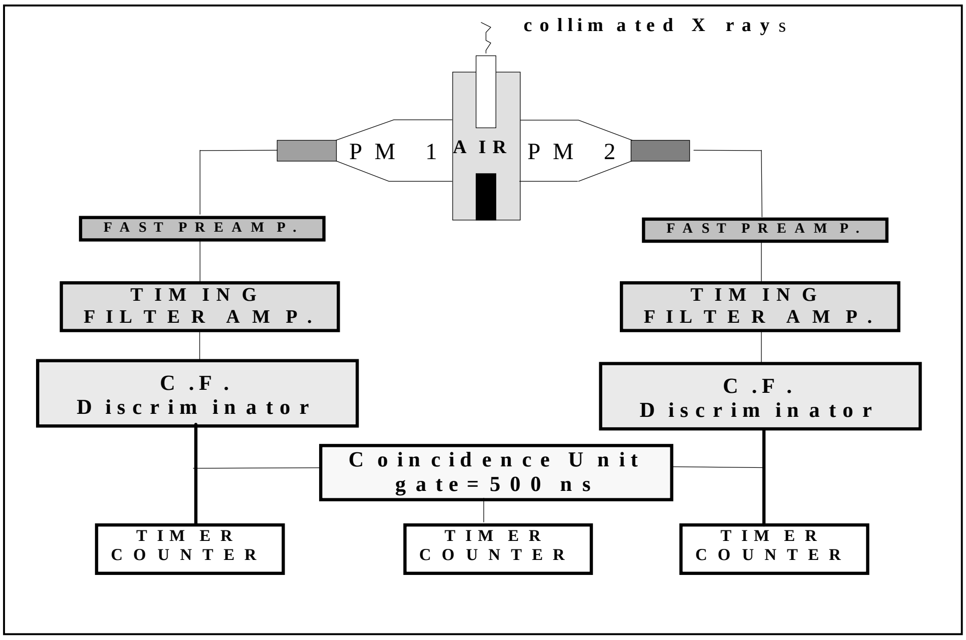

Fig. 2 The coincidence electronic chain.

We have used high gain settings and low discrimination thresholds (about 1/5 of the observed single photon peak) ; the collection efficiency was greater than 90 % (see paragraph 4).

Due to the low photoelectric cross section of air ($6.1 \cdot 10^{-4}$ cm^{-1}) and the small absorption region (4 cm) we used the intense X-ray source of the X-ray Beam Facility at LAX[11] in Palermo. The X-ray generator is a “Seyfert” tube (SN60), with flux ranging from 10^{10} to 10^{12} photons / sr $\cdot$ sec, covering the energy range from few keV to 25 keV depending of the target material used as anode in the tube. The collimated flux inside the gas cell was $2.7 \cdot 10^{6}$ photons / sec.

In the first run of the experiment we chosen the 22.1 keV fluorescence line of the Ag target with a trade-off between as much UV photons as possible inside the cell and a minimum X-ray Compton diffusion.

The UV yield measurements have been made in pure dry air (with impurity levels less than 1 ppm) and for comparison in 99.9999 % pure nitrogen. All measurements were made with a gas temperature of 295 ^{o}K.

A picture of the apparatus is shown in fig. 3.

3. THE UV FLUORESCENCE LIGHT YIELD

A semi-direct estimate of the UV fluorescence light yield can be obtained in all cases in which the detection efficiency (D_{eff}) is less than 1, as in our case.

D_{eff} is the ratio of the measured coincidence rate of the X-ray events detected as UV fluorescence photons (R_{coinc}) to the measured rate of the total X-ray photons absorbed in the gas cell ($R_{x\text{-}abs}$):

$$D_{eff} = \frac{R_{coinc}}{R_{x-abs}} \qquad (1)$$

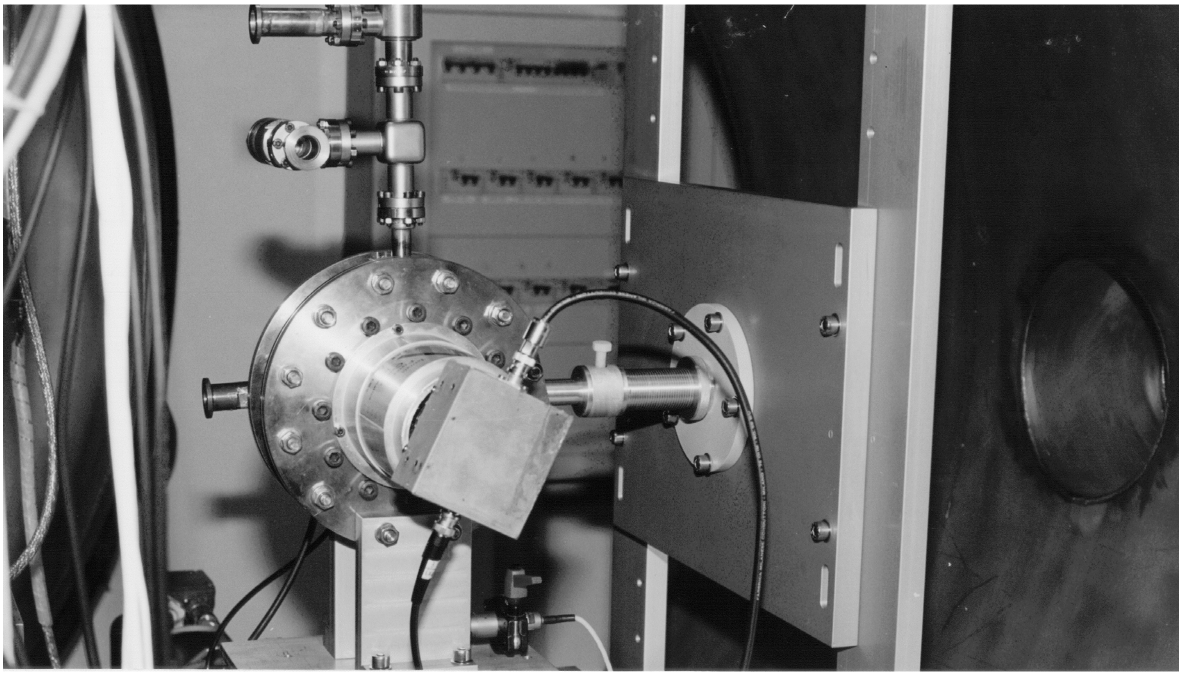

Fig. 3 A picture of the apparatus

The estimate of the light yield follows a statistical approach; the process starts by the emission of n_{uv} photons at the point at which the X-ray is absorbed and ends with the possible emission of one or more photoelectrons (n_e) at the cathode of the Pmt. For a single Pmt the probability of emission of k photoelectrons is given by the Binomial distribution:

$$P_{n_{uv}}(k) = \frac{n_{uv}!}{k! \cdot (n_{uv} - k)!} \cdot p_e^k \cdot (1 - p_e)^{n_{uv} - k}$$

where p_e is the probability that the emission of one UV photon is followed by the emission of one photoelectron:

$$p_e = t_w \cdot QE \cdot \Omega \qquad (2)$$

with:

t_w transmission of the quartz windows (detector and Pmt);

QE quantum efficiency of the photocathode;

Ω solid angle subtended by the Pmt at the UV light point production.

In our experiments two Pmts are used in coincidence and the probability of emission of k_1, k_2 photoelectrons from the photocathode of the Pmts is given by the multinomial distribution and under the hypothesis (well verified in our case) of $p_{e1} = p_{e2} = p_e << 1$ and $n_{uv} > 1$, it can be approximated by

$$P_{n_e}(k_1,k_2) = \frac{n_e^{(k_1+k_2)} \cdot e^{-2n_e}}{k_1! \cdot k_2!}$$

where

$$n_e = p_e \cdot n_{uv}$$

The probability P_{coinc} of a coincident signal from the two Pmts is thus given by the sum of all terms of $P_{ne}(k_1,k_2)$ excluding those for which k_1=0 or k_2=0.

Finally, if P_{ce} is the collection efficiency, the detection efficiency can be written as $D_{eff} = P_{coinc} \cdot P_{ce}$ and the formula for D_{eff} is:

$$D_{eff} = (1 - e^{2p_e} \cdot (1 + \frac{2 \cdot \sum_{k=1}^{n_{uv}} (p_e \cdot n_{uv})^k}{k!})) \cdot P_{ce} \qquad (3)$$

By measuring D_{eff} we can estimate n_{uv} and, therefore, the UV fluorescence *Ligth Yield*:

$$Light\ Yield = \frac{n_{uv} \cdot \varepsilon_{uv}}{\varepsilon_x} \qquad (4)$$

with:

ε_{uv} energy of the UV fluorescence line;

ε_x energy of X-ray photon.

4. EXPERIMENTAL RESULTS

The energy spectrum of the absorbed X-ray photons inside the gas cell is shown in fig. 4. This is the energy spectrum as measured by a Si detector normalized by the absorption efficiency of the air in the gas cell. The Ag-kα (22.1 keV) line is superimposed to a bremsstrahlung continuum which effective energy range is width only 20% of the Ag-Kα energy. We can assume, with reasonable error, a unique line of energy ε_x equal to the mean energy of the spectrum: $\varepsilon_x \cong 21$ keV.

In fig 5 is reported the measured coincidence rate of the X-ray events detected via UV fluorescence photons (R_{coinc}) as a function of filling pressure, in air and in pure nitrogen.
The R_{coinc} was obtained by measuring the rate of the coincidence signal of the two Pmts and by subtracting the background measured under the same conditions when no gas was present in the gas cell: $R_{coinc} = R_{p\neq 0} - R_{p=0}$

A contribution to the measured R_p^{meas} (from 10 % to 20%) comes from the random coincidences (R_{rc}) between the events detected by the two Pmts. This contribution has been evaluated and subtracted from R_p^{meas}**:** $R_p = R_p^{meas} - R_{rc}$

As the rate of the signals detected by the two Pmts (R_{pmt1}, R_{pmt2}) above the electronic lower threshold were in the range from 1000 to few thousands events per second and the time of the coincidence gate was $\delta\tau$ = 500 nsec**,** we have evaluated the contribution R_{rc} as: $R_{rc} = 2 \cdot R_{pmt1} \cdot R_{pmt2} \cdot \delta\tau$

At a given pressure we have evaluated the error by repeating several times the measurement. A systematic error of about 5-10% was found.

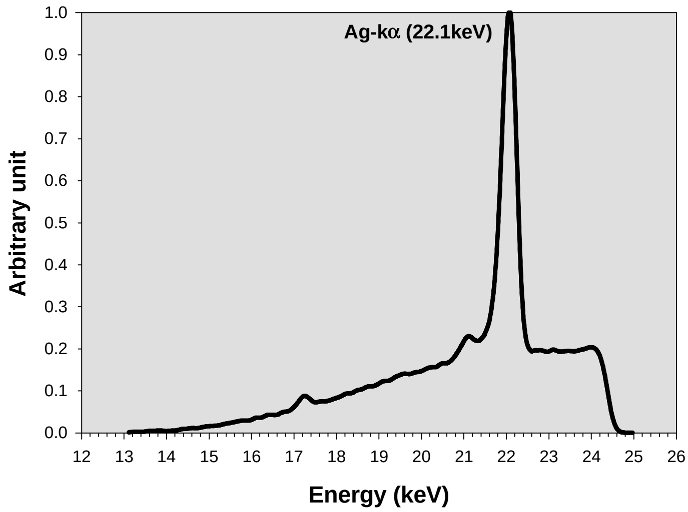

Fig. 4 The absorbed X-ray spectrum: The cut-off at 24.5 keV is due to a foil of 125 μm of Pd filter put before the collimator.

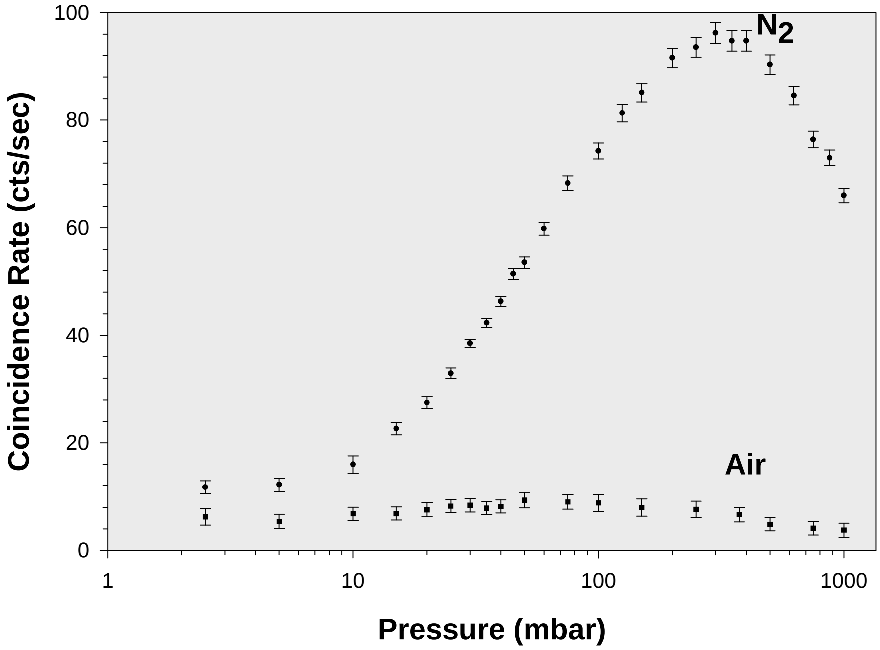

Fig. 5 The coincidence signals (R_{coinc}) count-rate as a function of pressure.

As we can see in fig. 5 the ratio of the counting rate of N_2 to air increases, from a factor of 2 up to ~ 20, by increasing the pressure. This is due to the increasing non radiative de-excitation of the N_2 molecules by collision with the O_2 molecules[10].

The rate of the X-ray photons absorbed in the gas cell $R_{x\text{-}abs}$ was estimated by measuring the X-ray flux with a fast scintillator (POLIPOP 0180) put in front the collimator. We found a flux of $2.7 \cdot 10^6$ photons/sec with an uncertain of about 10%.

The detection efficiency D_{eff} (shown in fig. 6) is, at any pressure, well below 100% (especially for air), indicating that few UV photons are produced inside the cell.

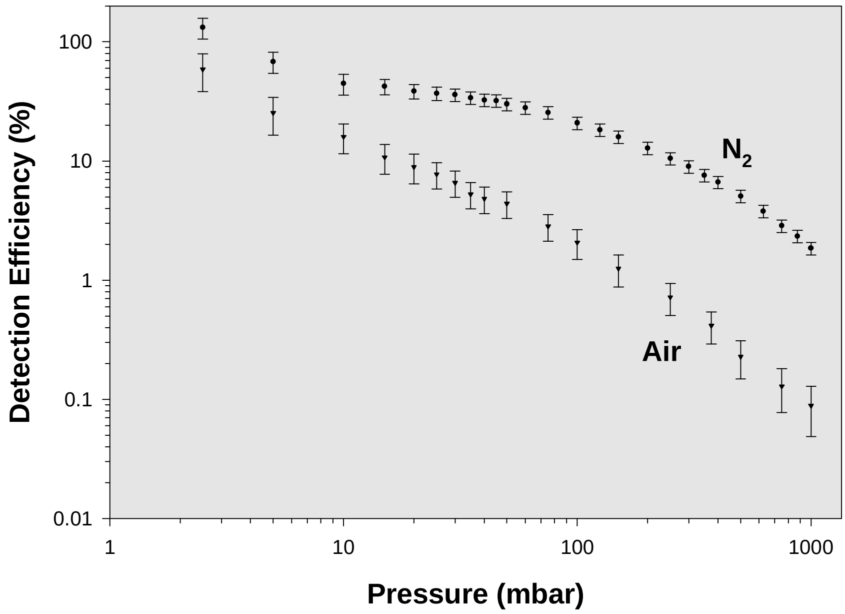

Fig. 6 The detection efficiency (D_{eff}) as a function of pressure.

The quantum efficiency (*QE*) of the two Pmts in the band of wavelengths 300 – 400 nm was measured at the laboratory of the Osservatorio Astrofisico di Catania[12] with an agreement between the two Pmts of ~ 10% (fig. 7). Within the same percentage there is an agreement also between the *QE* measured at the lab of Catania and that measured at the factory (Thorn EMI). So, we assumed in the calculation the average of the *QE*s with a 10% of systematic error.

The transmission of the quartz window t_w in the 300 – 400 nm band (as derived from typical transmission curves of commercially available samples)[13] is greater than 95%.

The collection efficiency P_{ce} can be evaluated taking into account the finite probability P_{np} that a photoelectron released at the photocathode of the Pmt doesn't propagate throughout the dynodic chain of the Pmt. With the high gains set in the preamps and amplifiers of the two branch of the electronic chain we can assume the efficiency of the electronic chain approximately equal to one and put $P_{ce} \cong (1 - P_{np})^2$. The gain of each Pmt was set as higher as compatible with dark count (background). They were operate at 2 kV. The computation of P_{np} have been made starting by the Polya distribution[14] that govern the statistic of the electrons emitted from the dynodes. In the calculus we have used a gain of 6.5 and 4.1 for the first and the remaining 11 stages respectively (these being the relevant values for BeCu dynodes of our Pmts operated at a voltage of 300 and 150 volts respectively)[15] and a parameter b = 1 that is the worst case but near the effective value for the our Venetian Blind type Pmts. We found $P_{np} \sim 0.05$ and $P_{ce} \geq 90$ %.

Finally for the energy of the UV photons ε_{uv} we assume: ε_{uv} = 3.68 eV (corresponding to the line at 337 nm). In our experiment, in fact, we expect that the primary photoelectron, produced after the absorption of the X-ray photon, generates secondary electrons with energy of few tens eV. These excite mainly the first level of the N_2 second positive (2P) system[10]:

$$N_2 + e \rightarrow N_2^*(^3\Pi_u) + e$$

The de-excitation of this level is followed by the emission of a photon with a wavelength of 337 nm.

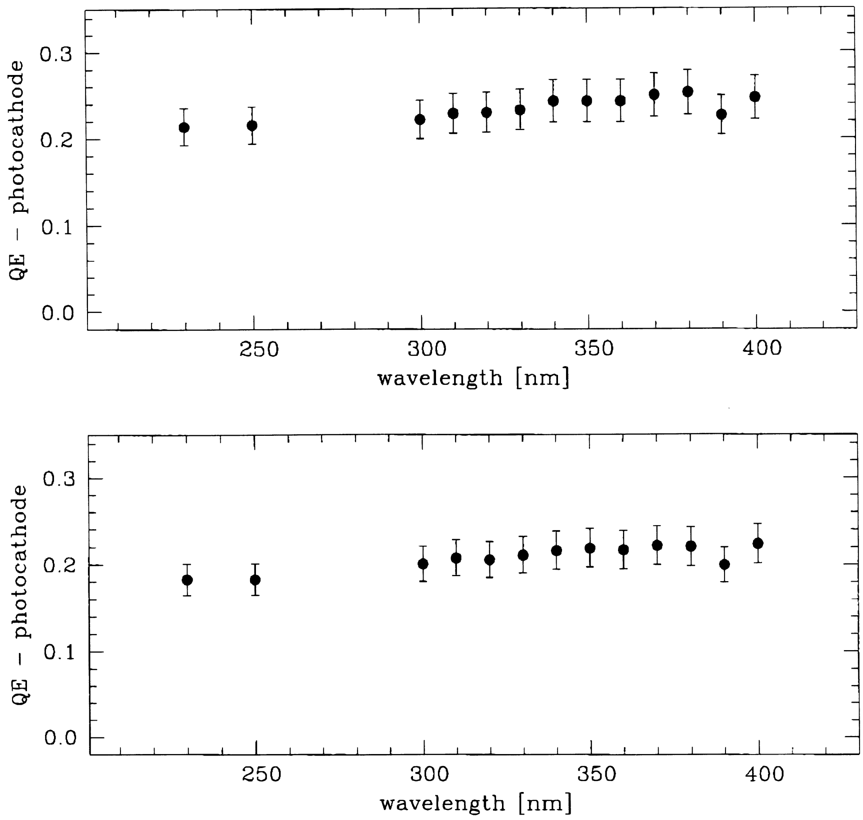

Fig. 7 The Quantum Efficiency of the two Pmts.

The number of UV fluorescence photons n_{uv} produced and therefore the UV fluorescence *Light Yield* was evaluated by the formulas (2), (3) and (4).

The UV fluorescence Light Yield as function of the filling pressure for air and pure nitrogen is finally shown in fig. 8. The measured UV yield follows a proportional inverse law with the pressure both for air and for pure nitrogen. This is expected from the kinetic theory, taking into account that the non radiative collisional de-excitations increase as the increasing (density) pressure[10].

Below ~ 10 mbar, however, the measured UV yields are higher than predicted by the p^{-1} law. Moreover, in the case of pure nitrogen the detection efficiency at 2.5 mbar was a little higher than 1 (see fig. 6). Furthermore, repeating several time the measure below 10 mbar we obtained in same cases detection efficiency well above than 1. A visual inspection at the oscilloscope of the pulses at the output of the Pmts showed extra coincidence signals after few µsec from the UV coincidence event. At this moment the phenomenon is not well understood.

We have repeated at a different pressure values (both in air and in pure nitrogen) the same measurements placing outside of each of the two quartz windows of the gas cell a square shaped blue bandpass BG1 filter (3 mm thick, 5 cm of side) whose transmission is limited to the band of wavelength between 300 and 400 nm. Each BG1 filter covered only $^1/_2$ of the photocatode area while the remaining part was obscured by opaque material. We repeated again the measurements removing only the BG1 filters. The two set of values of coincidences were under the experimental errors the same, confirming that the wavelength of the radiation produced inside the gas cell is within the bandpass of the filters. Of course, at any pressure we obtained ∼ $^1/_3$ of the UV coincidence count rate measured at full photocathode area, but if we take into account the different total solid angle subtended by the Pmts at the UV production site we obtain exactly the same value of UV fluorescence Light Yield as reported in fig. 8. Finally, we replaced each quartz window with a Plexiglas (4 mm thick) of the same diameter which has a transmission cut-off below 390 nm and a 30% of transmittance at 391 nm, that is the wavelength of the line produced by the de-excitation of the first excited level of the N_2^{+*} molecular ions. At all pressure the UV coincidence count-rate dropped to zero.

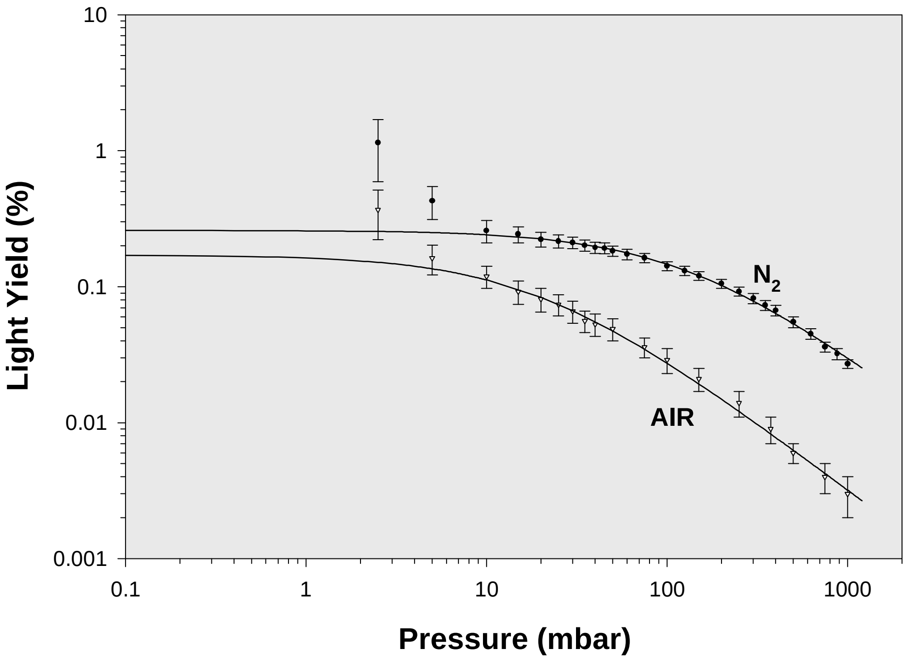

Fig. 8 The UV Fluorescence Light Yield as a function of pressure fitted with a p^{-1} law.

5. CONCLUSIONS

The air fluorescence UV light yield for X-ray (≅ 21 keV) excitation has been measured ranging from 0.18 % to 0.07 % for the air pressure varying from 1 mbar to 30 mbar at T = 295 °K. A weak dependence from T is expected and therefore the measurements will be extended for the temperature interval 200 °K – 300 °K to explore the conditions present in the atmosphere for the region interested by the absorption of the GRBs. The energy range extending from 1 keV to 100 keV will also be investigated.

It appears that in AIRWATCH FROM SPACE experiment, GRBs are detectable with good efficiency down to fluence values of ∼ 10^{-7} erg cm^{-2}. This is of particular interest to investigate the possible existence of coincidence between EECR neutrinos and GRBs; The source directional capability, for GRBs of the proposed AIRWATCH experiment, will require an external input for the GRB arrival direction, should the time coincidence be delayed because of a neutrino mass value different from zero or a neutrino emission during the afterglow following the GRB itself.

6. ACKNOWLEDGEMENTS

We would like to thank the whole AIRWATCH FROM SPACE collaboration and in particular Prof. John Linsley, Prof. Livio Scarsi and Dr. Bruno Sacco for they continuous encouragement and support. We would like to express also our thanks to G. Agnetta, B. Biondo, R. Di Raffaele, A. Mangano and M. Quartararo for their assistance and technical support.

7. REFERENCES

1. R.M. Baltrusaitis *et al.*, *Nucl. Instr. & Meth.*, **A 240**, pp. 410- , 1985.

2. D.J. Bird *et al.*, *23th ICRC*, Calgary, **2**, pp. 450- ,1993.

3. M. Al-Seady, D.J. Bird *et al.*, *Proc. Of Intern. Symp. On Extremely High Energy Cosmic Rays: Astrophysics and Future Observatories*, Tokyo, pp. 191-204, 1996.

4. J. Linsley, *Proc. Work. On Very High Energy Cosmic Ray Interactions*, Univ. Of Pennsylvania, pp. 476-491, 1982.

5. L. Scarsi *et al.*, "AIRWATCH: a space mission to observe the UV fluorescence induced in the Earth atmosphere by the Extreme Energy Cosmic Radiation.", *these Proceedings*, 1998.

6. G. Davidson and R. O'Neil, *J. Chem. Phys.*, **41**, pp. 3946- , 1964.

7. F. Kakimoto, E.C. Loh, M. Nagano, H. Okuno, M. Teshima, S. Ueno, "A measurement of the air fluorescence yield", *Nucl. Instr. & Meth.*, **A 372**, pp. 527-533, 1996.

8. S. Giarrusso, G. Manzo, S. Re, "A primary scintillation gated high pressure position sensitive gas scintillation proportional counter (HPGSPC) for applications to x-ray astronomy", *Proc. SPIE*, **597**, pp. 217-221, 1985.

9. B. Biondo, O. Catalano, F. Celi, G. Fazio, S. Giarrusso, G. La Rosa, A. Mangano *et al.*, "Air Fluorescence efficiency measurements for AIRWATCH based mission: Experimental set-up", *Proc. Of Conf. On Observing Giant Cosmic Ray Air Showers for* $E>10^{20}$ *eV Particles from Space*, to be published by American Institute of Physics, College Park – Maryland, November 13-15, 1997.

10. A.N. Bunner, "Cosmic ray detection by atmospheric fluorescence", *Ph.D. Thesis*, Cornell University, Ithaca – NY, 1967.

11. F. Celi, L. Dalla Bella, S. Ferrari, S. Re, G. Richiusa, L. Scarsi, "The X-ray Facility at LAX in Palermo", *Vakuum in Forschung und Praxis*, **1**, pp. 21-24, 1996.

12. G. Bonanno, P. Bruno, A. Cali, R. Cosentino, R. Di Benedetto, M. Puleo, S. Scuderi, " The Catania Astrophysical Observatory Facility for UV CCD Characterization", *SPIE Proc.*, **VOL 2808**, August 1996

13. *Heraus Quartz* catalogue.

14. J.R. Prescott, "A statistical model for photomultiplier single-electron statistics", *Nucl.Instr. & Meth.*, **39**, pp. 173-179, 1966.

15. *Thorn EMI photomultipliers* catalogue.